Acta Geodyn. Geomater.Vol.2, No.1 (137), 13-23, 2005

MONITORING OF STRAIN ACCUMULATION ALONG ACTIVE FAULTS IN THE EASTERN GULF OF CORINTH: INSTRUMENTS AND NETWORK SETUP

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(*Received* August2004*, accepted* November 2004)

ABSTRACT
The eastern Gulf of Corinth contains several active fault segments that accommodate N-S extensional strain. In 1981 three large earthquakes ruptured faults onshore including the south-dipping Kaparelli fault. Earthquake ruptures resulted in metric-scale ground displacements which were well mapped and supply an excellent dataset for fault slip directions and strain patterns. In addition, recent geological data showed that the Kaparelli area forms the boundary between fast-slipping normal faults in Corinth-Perachora regions and slow-slipping faults in Viotia, Attica. In order to measure the kinematics of deformation in 3-D our group has installed a dense GPS network and two extensometers. This paper reports details of this research effort along with some first results.

KEYWORDS: Active faults, Gulf of Corinth, strain, GPS

1. INTRODUCTION

The Gulf of Corinth in central Greece is one of the most tectonically active and rapidly extending regions in the world (10-14 mm/yr; Billiris et al., 1991). Surface topography and geomorphology are clearly associated with seismic activity along large normal faults (Fig. 1; Armijo et al., 1996; Roberts and Koukouvelas, 1996). Extension is mainly directed N-S (Billiris et al., 1991; Clarke et al., 1998). The southern side of the Gulf of Corinth is bound by a series of major north-dipping normal faults, forming a complex asymmetric half graben (Jackson et al., 1982; Roberts, 1996). There are E-W striking normal faults with antithetic dip, i.e. to the south; however, they are visible at the northern edge of the Gulf.

In 1981 a sequence of three earthquakes with magnitudes greater than 6 struck the eastern Gulf of Corinth. The first two (Ms 6.7, 6.4) occurred during the night of the 24th-25th February and the third (Ms 6.4) seven days later on the 4th of March (Hubert et al., 1996). North-dipping surface breaks were noted the morning after the first two events on the southern side of the Gulf (Perachora Peninsula) and south-dipping ruptures appeared on the northern side of the Gulf (Kaparelli region) as a result of the third event (Fig. 2; Jackson et al., 1982). In both areas seismic motion occurred along basin-bounding faults bringing in contact Mesozoic limestones and alluvial deposits as well as colluvium.

Focal mechanisms of small and shallow earthquakes (Hatzfeld et al., 2000) also show normal faulting with the active fault plane dipping at about 45° for faults at the eastern end of the Gulf of Corinth including Kaparelli. Recently, three trenches have been excavated across the Kaparelli Fault (Pavlides et al., 2003). Their stratigraphic record shows at least three events during the Holocene period, with the 1981 event included. The estimated slip rate is 0.28 mm/yr. Colluvial tectonostratigraphy and analysis of displacements on key horizons suggests surface rupturing events in the order of 0.7-1 m.

Our group has begun monitoring of the Kaparelli fault area since May 2003. On May 26, 2003 we installed a TM-71 extensometer. A second instrument was installed on July 15, 2004. In addition, we installed a dense GPS network comprising six stations. The network was set up on November 11-12, 2003 and first measurement took place in May 2004. In this paper we present details on network instrumentation and geometry along with some preliminary results.

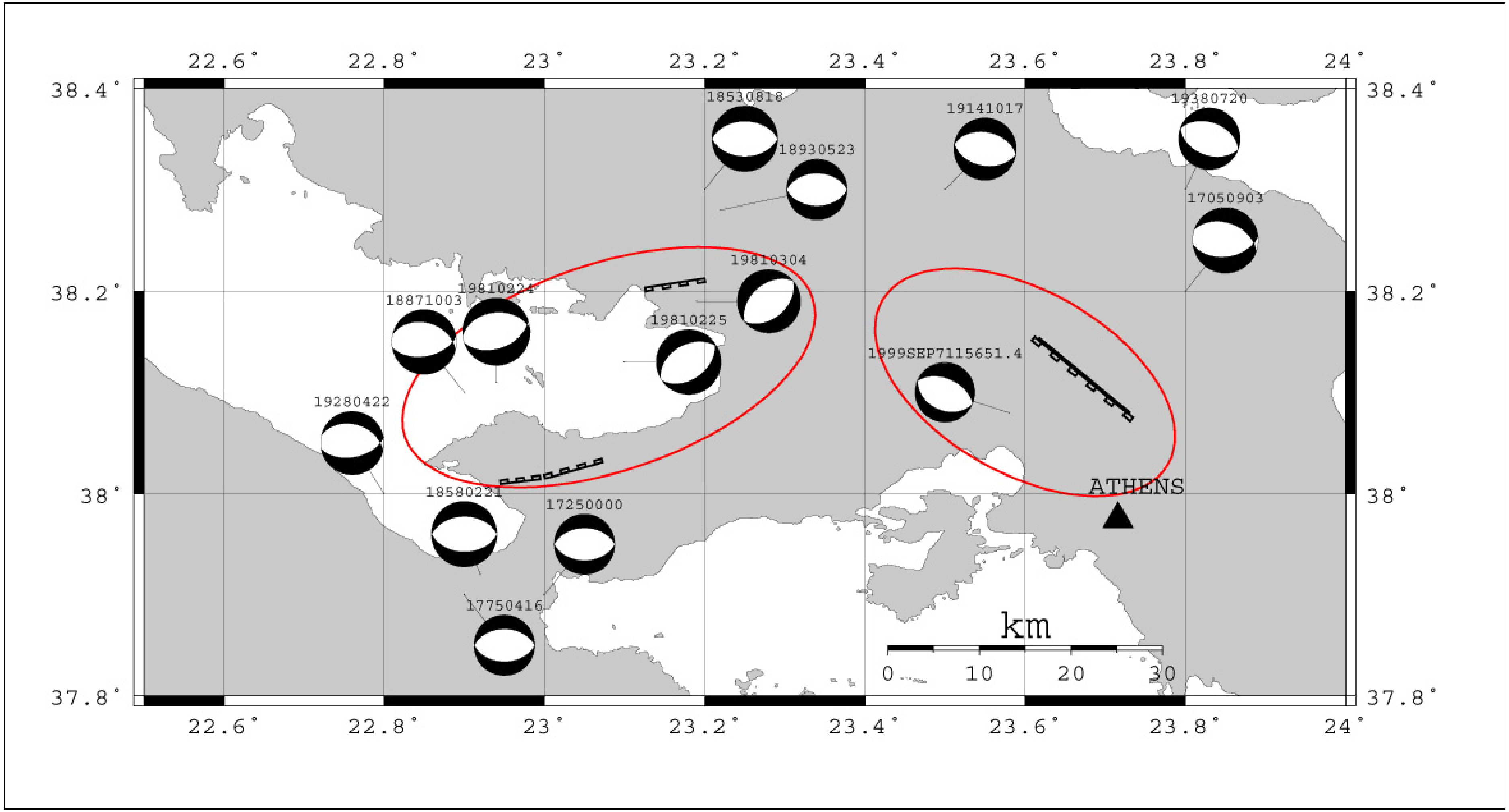

Fig. 1 Seismicity map of the eastern Gulf of Corinth and Attica regions since 1700 showing events ≥ 5.9Ms. Ellipses indicate rupture zones of the 1981 and 1999 earthquakes. These zones differ in both location and trend (NE-SW for Corinth vs. NW-SE for Attica). Beachballs indicate fault plane solutions with black colour indicating compression.

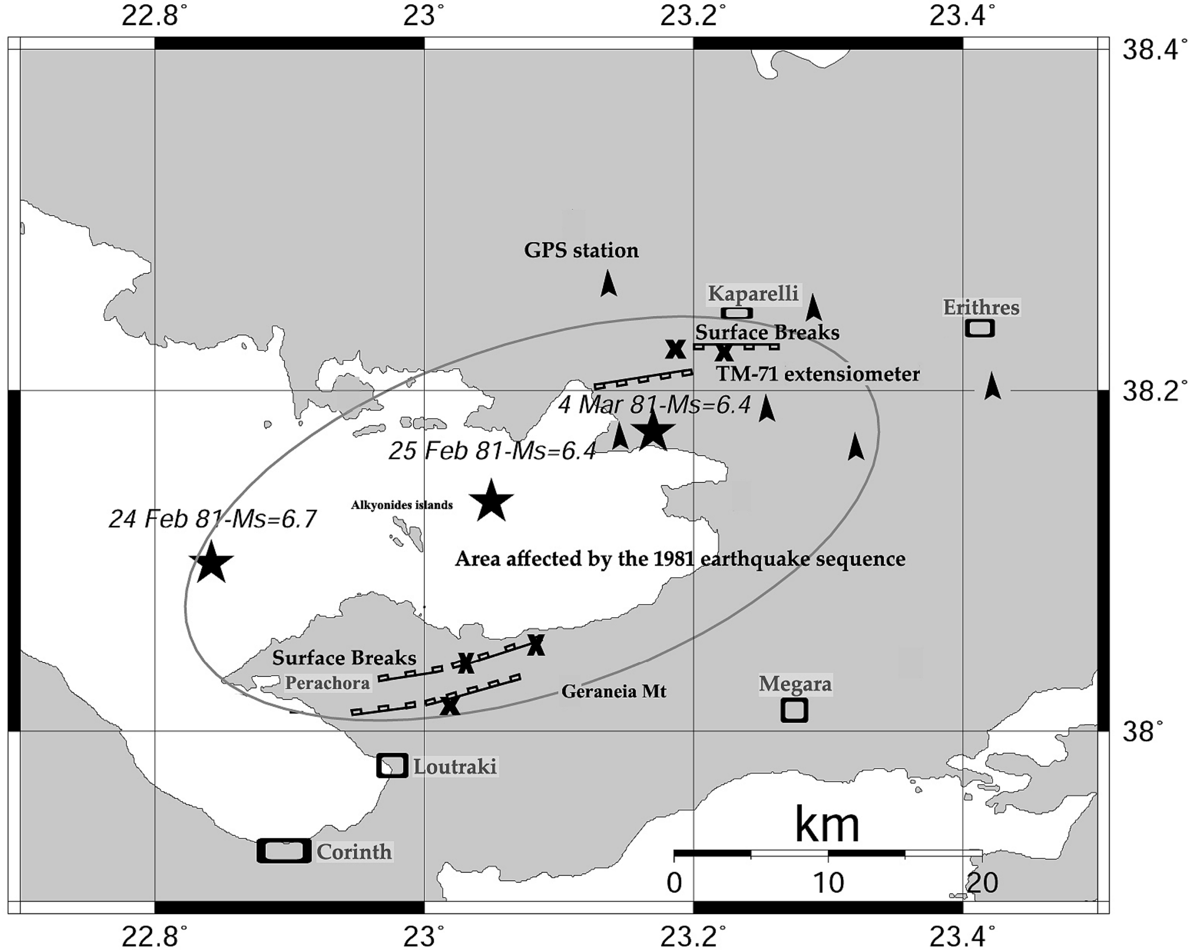

Fig. 2 Map of the study area showing epicentres of the 1981 earthquake sequence (stars). X signs point to TM-71 instrument locations and black arrows indicate locations of the non-permanent GPS stations. Open rectangles show large towns and villages.

2. GEOLOGICAL SETTING

The E-W trending Kaparelli Fault is a segment of a greater normal fault zone that is situated to the north of Parnitha Mountain in Central Greece. This zone extends from the eastern part of the Gulf of Corinth to the South Gulf of Evia (Fig. 1). In this zone, most faults dip to the north, however, the Kaparelli fault ruptured in 1981 by down-throwing to the south. The co-seismic slip vector was directed at 200-220^o / 60-70^o (dip direction / dip angle).

The Kaparelli Fault consists of three segments, two of which were ruptured in 1981 (Jackson et al. 1982). The two-ruptured segments form left-stepping en echelon geometry, while the third northwestern segment of the fault didn't rupture (Fig. 3). The fault segments are clearly expressed at the surface by nearly continuous scarps. The footwall elevation is 600 m and lithology is composed of hard, Mesozoic limestones. The hanging wall block forms a small basin and contains approximately 200 m of fluvial-terrestrial deposits of Pleistocene age as well as Holocene alluvium.

The surface breaks of March 4, 1981 comprised two continuous fault segments (Jackson et al. 1982). The first lies immediately south of Kaparelli village and forms a continuous limestone scarp for about 5 km. Scarp freshness and existence of basal stripes showing different shades of grey suggest that the 3 to 4 m high scarp is the cumulative effect of many earthquake events. Recent displacements on this segment average 50-70 cm, as it is clearly visible by at least two discontinuous basal stripes of bedrock. This observation was confirmed by paleoseismic results (Pavlides et al., 2003). At its eastern termination the 1981 rupture turned abruptly in an SE direction and crossed recent alluvial sediments of the valley floor for a few hundred meters.

3. DEFORMATION MONITORING

TM-71

In May 2003 and July 2004 we installed two TM-71 extensometers (Fig. 4a) along the Kaparelli fault. The 2003 installation was done at the trench Kap2 that was excavated across the fault (Pavlides et al., 2003). The TM-71 is fixed to the fault (north side) and to a construction built on the hanging wall (south side) by steel bars. The 2004 installation was done against a free surface of the fault plane, about 2 km to the west of locality Kap2. The TM-71 instrument is based on the mechanical-optical interference principle (moiré pattern; Košťák and Cruden, 1990). It allows an observation of movements in three orthogonal directions at a resolution better than 0.1 mm/yr. It can measure micro-displacements along three directions by using 2 perpendicular moiré indicators. The position of the x, y, and z axes of the instrument corresponds respectively to: (X) the direction perpendicular to the fault or fault-normal motion, (Y) direction parallel to fault strike or the strike slip motion along the fault surface and (Z) vertical direction or the dip slip component of motion. This allows for 3-D monitoring at sub-millimeter scale. The instrument readings are recorded on a monthly basis by NOA. The recording is done by taking high-resolution photographs of the fringes of both faces of the instrument. The digital pictures are then analysed for the detection of displacements (Košťák and Cruden, 1990).

Despite the fact that measuring period is only 15-months old it is possible to see a preliminary result (Fig. 5). Practically, the only small recorded displacement is along the axis "X". Up to the August 2003 the opposite walls (footwall and hanging wall) have been compressed because their distance was reduced (by about 0.5 mm – summer period). After that the reduction changed to widening (expansion). Another change in direction of displacement has been recorded in the middle of December 2003. Thus, the graph starts to show seasonal variations, which is usual. Nevertheless, at the end of first year of observations (compare 06.2003 with 06.2004) we register opening by –0.3mm per year. Movement along the axis "Z" (vertical) as well as along the axis “Y” (horizontal; along the fault strike) is negligible up to now, trends have not been established yet.

GPS

In November 2003 we have installed a dense geodetic network (Fig. 2; Table 1) using the satellite Global Positioning System (GPS) at six sites in the Eastern Corinth Gulf (KAPNET). All benchmarks are drilled on limestone bedrock. The network was set up to obtain a better definition of the motion of the crustal blocks on either side of the Kaparelli Fault and Kithairon Mountain (Fig. 6). This motion can be described in a first approximation by a combination of translation and rotation. By combining the displacement vectors obtained at points of successive GPS campaigns during 2004, 2005 and 2006 we will compute the velocity field over the Eastern Corinth Gulf. In addition, we will calculate the normal and shear strain rate components associated with the Kaparelli fault and compare these qualitatively with seismological data from the NOA network. The network was measured for the first time in May 2004 using ASTHECH receivers. In particular stations ERIT, KAPA and TAPS (Fig. 4b) were surveyed using ASHTECH Zxtreme instruments and ASH701975.01A antennas where remaining stations were surveyed using Z-XII instruments and ASH700718B antennas. Station AGTR (Figure 6) was used as the base station.

During May 2004 we conducted our first measurement campaign and the data were processed by use of the Bernese 4.2 Software. The Earth rotation parameters were adopted from the International GPS Service (IGS) and the calibration of antenna phase centers according to the IGS-01 and NGS. The

Fig. 4 Field photographs of deformation monitoring instruments. a) TM-71 installation inside trench Kap2 (May 2003; see Fig. 2 for location). b) GPS antenna and receiver in operation near the Agios Vasilios Bay (Station TAPS; May 2004).

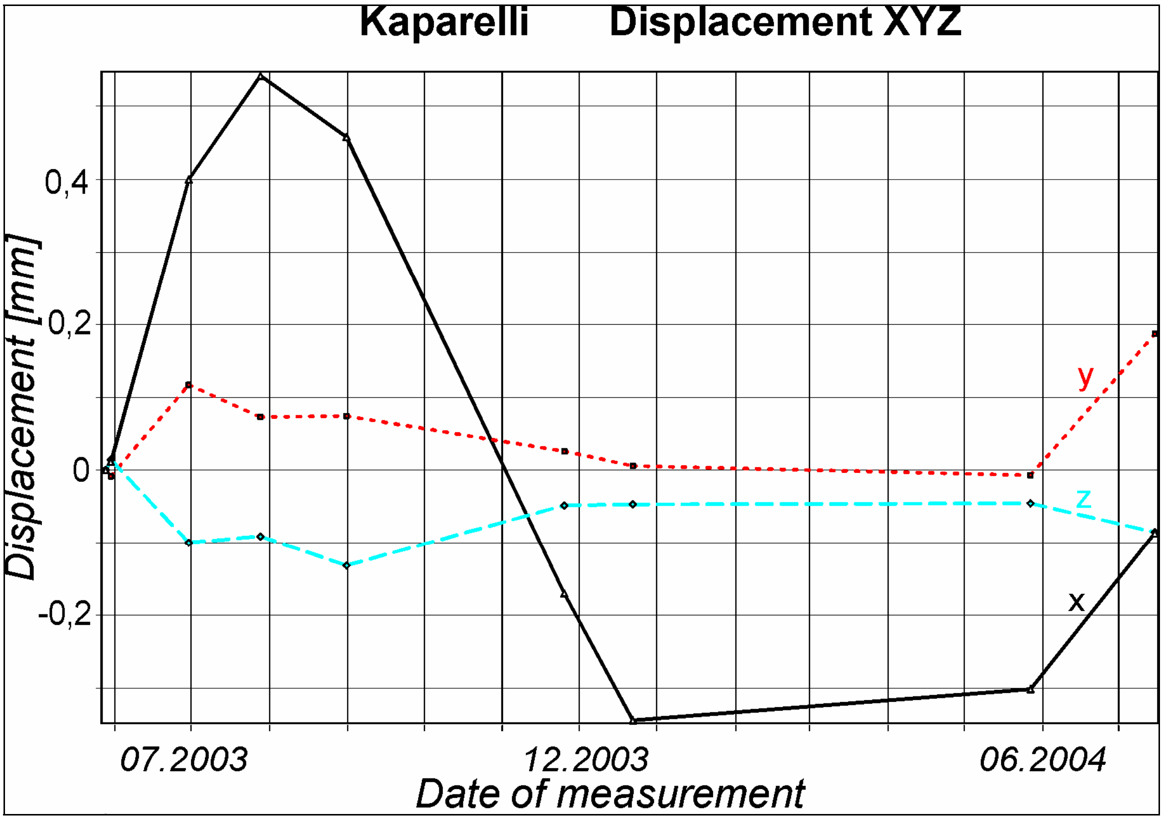

Fig. 5 Displacement – Time diagram for site Kap2 along the Kaparelli Fault. X direction measures displacement across the fault plane, Y direction along the fault plane and Z along the vertical direction, respectively.

Table 1 The coordinates of KAPNET Stations

Nr[1]	DATE[1]	NAME[1]	LATITUDE[1]	LONGITUDE	ALT[1]
1	11-11-03	**AGTR**	38° 12′ 29.3″	23° 14′ 14.0″	548
2	12-11-03	**VILI**	38° 10′ 07.9″	23° 18′ 11.2″	667
3	12-11-03	**KAPA**	38° 13′ 52.6″	23° 13′ 18.9″	312
4	12-11-03	**TAPS**	38° 11′ 47.8″	23° 08′ 45.2″	456
5	12-11-03	**ACLA**	38° 14′ 20.4″	23° 10′ 01.7″	444
6	12-11-03	**ERIT**	38° 12′ 47.9″	23° 20′ 21.5″	443

[1]GPS point number [2]Date of Installation [3] Name after closest mountain ridge, village or town [4]degrees, datum WGS84
[5]Altitude in m

Troposphere model Saastamoinen was used a priori (the standard atmosphere) without meteorological data with the Niell mapping function. Residual atmosphere zenith delays were estimated for two-hour intervals. The ionosphere was eliminated using the ionosphere free linear combination. For phase ambiguity determination the models from the Local Analysis Center of EPN network - Warsaw University of Technology (WUT) and CODE were used. All KAPNET positions were resolved with Root-Mean-Square residuals less than 1 mm.

4. FUTURE WORK – CONCLUSIONS

GEODETIC STRAIN AND HOLOCENE FAULTING

Our first priority is to establish both the magnitude and direction of geodetic strain and compare it with the Holocene faulting record as published in Pavlides et al. (2003). The orientation of the strain axes will be also compared with the configuration of the rupture zones of both the 1981 and the 1999 earthquakes (Fig. 1). A second point is to locate the strain rate transition because the greater Kaparelli region is found in a key position in terms of strain localisation. The large E-W faults of the Gulf of Corinth slip fast (1-2 mm/yr) and terminate towards the south of the Kaparelli Fault, while the large normal faults of the Parnitha region to the east slip at about five (5) to ten (10) times less (0.2-0.4 mm/yr; Ganas et al., 2004; Fig. 1). It is interesting to map this transition in fault slip rates by using the GPS measurements of KAPNET. A third point concerns the total offset on the Kaparelli fault that is small (< 200 m), while the geological data suggest that it is segmented (Fig. 3). So our measurements will differentiate fault slip and strain accumulation among the segments. These observations will also shed light into fault growth processes as Kaparelli is an early phase in the development of large normal faults that involves the merging of two or more faults of differing strikes, rather than the steady lengthening of a single fault segment.

Previous GPS work in the region by Clarke et al. (1995) was able to calculate a complex mechanism for the (1981/03/04) event. The mechanism consists of two double-couple sources on neighbouring fault segments and fits the geodetic data better, while the resultant fault breaks and slip directions agree with field observations (Fig. 3). The strain in the interval 1981-1991 was interpreted as a combination of post-seismic relaxation of strain upon a regional accumulation of extensional strain. Similar measurements of crustal strain from KAPNET will investigate if 1981 post-seismic strain still exists. In such a case the measurements may be interpreted as reflecting visco-elastic relaxation of a layer underlying the elastic upper crust, in which case a lower bound on the viscosity of this layer may be obtained.

USE OF EXTENSOMETERS

We are also interested in the use of extensometers such as TM-71 in measuring 3-D strain across normal faults. Three (3) similar instruments have been installed in the Perachora peninsula by Maniatis et al., (2003; Fig. 2). Given that fault slip rates at these localities differ by a factor of five (5) or even more it is important to compare 3-D strain measurements in order to estimate inter-seismic strain accumulation along the two fault zones.

Another issue concerns the identification of instrument-induced errors on our measurements and their estimation. The advantage that TM-71 has no electronic parts is counterbalanced by the infinitesimal deformations caused by climatic fluctuations (precipitation, temperature). For example a seasonal effect along the X-axis is seen in the 16-year data series from the Simitli graben in SW Bulgaria (Dobrev and Košťák, 2000).

ACKNOWLEDGEMENTS

This work has been supported by the COST Action 625 “3-D Monitoring of Active Tectonic Structures”, the General Secretariat for Research and Technology of Greece and the National Observatory of Athens. We thank one anonymous reviewer for comments and Dr Zdenka Schenkova for editorial assistance. We are indebted to George Stavrakakis, Luigi Piccardi, Spiros Pavlides, Anastasia Kiratzi and Yannis Koukouvelas for discussions. We also thank the NOA technical Staff, George Michaletos and Theodoros Vourakis for field assistance. Figures 1 and 2 were made with GMT.

REFERENCES

Armijo, R., Meyer, B., King, G.C.P., Rigo, A. and Papanastasiou, D.: 1996, Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean. Geophys. J. Int. 126, 11–53.

Billiris, H., Paradissis, D., Veis, G., England, P., Featherstone, W., Parsons, B., Cross, P., Rands, P., Rayson, M., Sellers, P., Ashkenazi, V., Daavison, M., Jackson, J. and Ambraseys, N.: 1991, Geodetic determination of tectonic deformation in Central Greece from 1900 to 1988. Nature 350, 124–129.

Clarke, P., Curtis, A., England, P., Parsons, B., Paradissis, D., Veis, G. and Billiris, H.: 1995, Geodetic determination of strain during the seismic cycle: Results from the Alkyonides Region, Central Greece. TERRA abstracts, Abstract supplement No. 1 to TERRA Nova 7, 35-35.

Clarke, P.J., Davies, R. R., England, P. C., Parsons, B., Billiris, H., Paradissis, D., Veis, G., Cross, P. A., Denys, P. H., Ashkenazi, V., Bingley, R., Kahle, H. G., Muller M. V. and Briole, P.: 1998, Crustal strain in Central Greece from repeated GPS measurements in the interval 1989-1997. Geophysical. J. Int., 135(1), 195-214.

Dobrev, N. and Košťák, B.: 2000, Monitoring tectonic movements in the Simitli graben, SW Bulgaria. Engineering Geology, 57(3-4), 179-192.

Ganas, A., Pavlides, S. B., Sboras, S., Valkaniotis, S., Papaioannou, S., Alexandris, G. A., Plessa, A. and Papadopoulos, G. A.: 2004, Active fault geometry and kinematics in Parnitha Mountain, Attica, Greece. Journal of Structural Geology, 26, 2103-2118.

Hatzfeld, D., Karakostas, V., Ziazia, M., Kassaras, I., Papadimitriou, A., Makropoulos, K., Voulgaris, N. and Papaioannou, Ch.: 2000, Microseismicity and faulting geometry in the Gulf of Corinth (Greece). Geophysical J. Int., 141, Issue 2, 438, doi:10.1046/j.1365-246x.2000.00092.x

Hubert, A., King, G., Armijo, R., Meyer, B. and Papanastasiou, D.: 1996, Fault re-activation, stress interaction and rupture propagation of the 1981 Corinth earthquake Sequence. Earth Planet. Sci. Lett., 142, 573-585.

Jackson, J.A., Gagnepain, J., et al.: 1982, Seismicity, normal faulting and the geomorphological development of the Gulf of Corinth (Greece): the Corinth earthquakes of February and March 1981. Earth Planet. Sci. Lett., 57, 377– 397.

Košťák, B. and Cruden, D.M.: 1990, The Moiré crack gauges on the crown of the Frank Slide. Can. Geotech. J., 27, 835-840.

Maniatis, G., Lempp, CH. and Heinisc, H.: 2003, 3D strain monitoring of onshore active faults at the eastern end of the Gulf of Corinth (Greece). J. Geodynamics, 36, 95 – 102.

Pavlides, S., Koukouvelas, I., Ganas, A., Kokkalas, S., Tsodoulos, I., Stamatopoulos, L., Goyntromichou, C. and Valkaniotis, S.: 2003, Preliminary palaeoseismological results from the Kaparelli fault (Central Greece). Geophysical Research Abstracts, 5, 07069, European Geophysical Society.

Roberts, G.P.: 1996, Non-characteristic normal faulting surface ruptures from the Gulf of Corinth Greece. Journal of Geophysical Res. 101 (25), 255–267.

Roberts, G.P. and Koukouvelas, I.: 1996, Structural and seismological segmentation of the Gulf of Corinth fault system: implication for models of fault growth. Annali di Geofisica 3, 619–646.

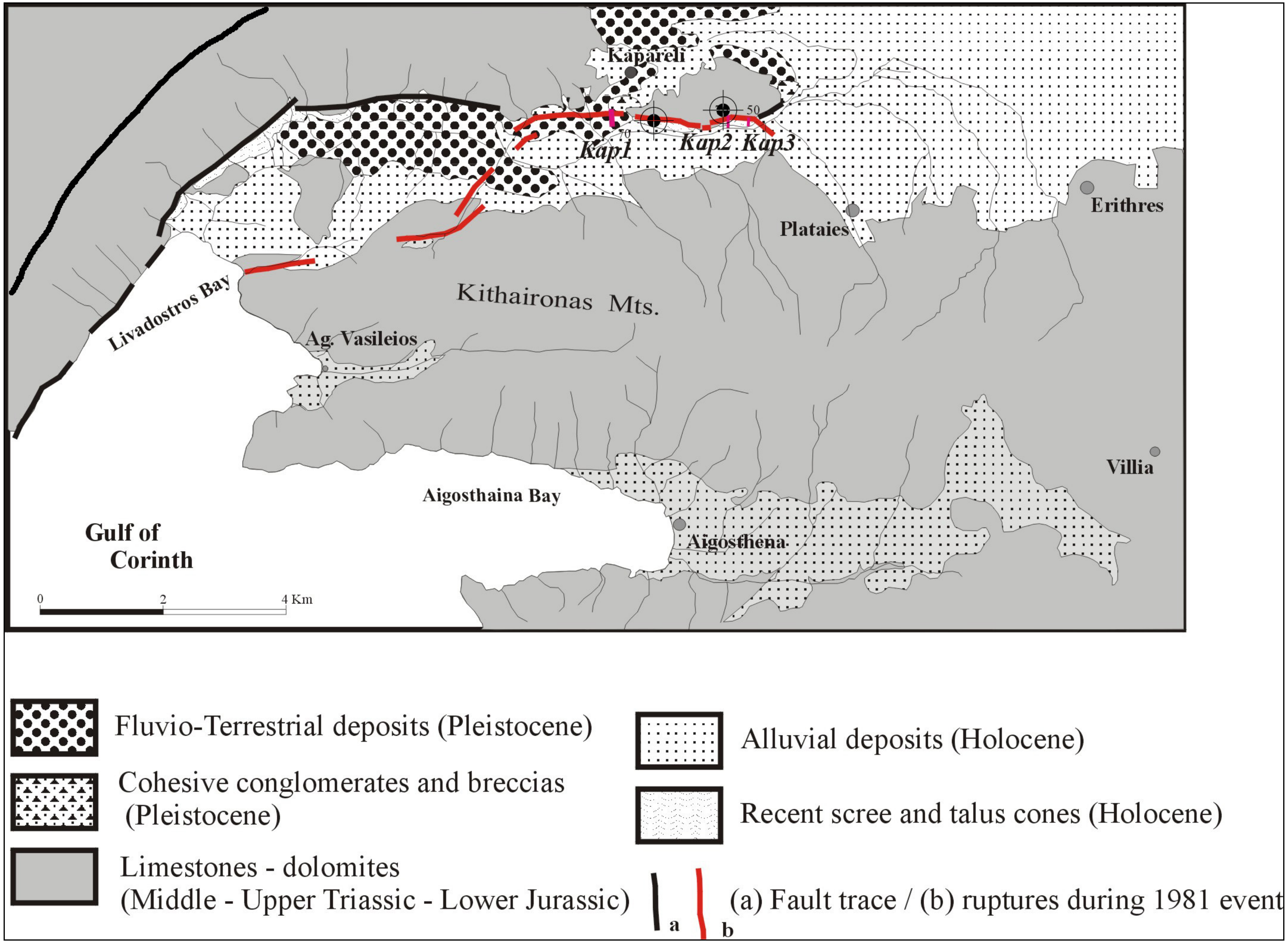

Fig. 3 Geological map of the Kaparelli area, central Greece. The 1981 ruptures are shown in red. Displacement is to the south. Trench positions are denoted by Kap1, Kap2 and Kap3. Circle symbols point to TM-71 installations. Map after Pavlides et al., 2003.

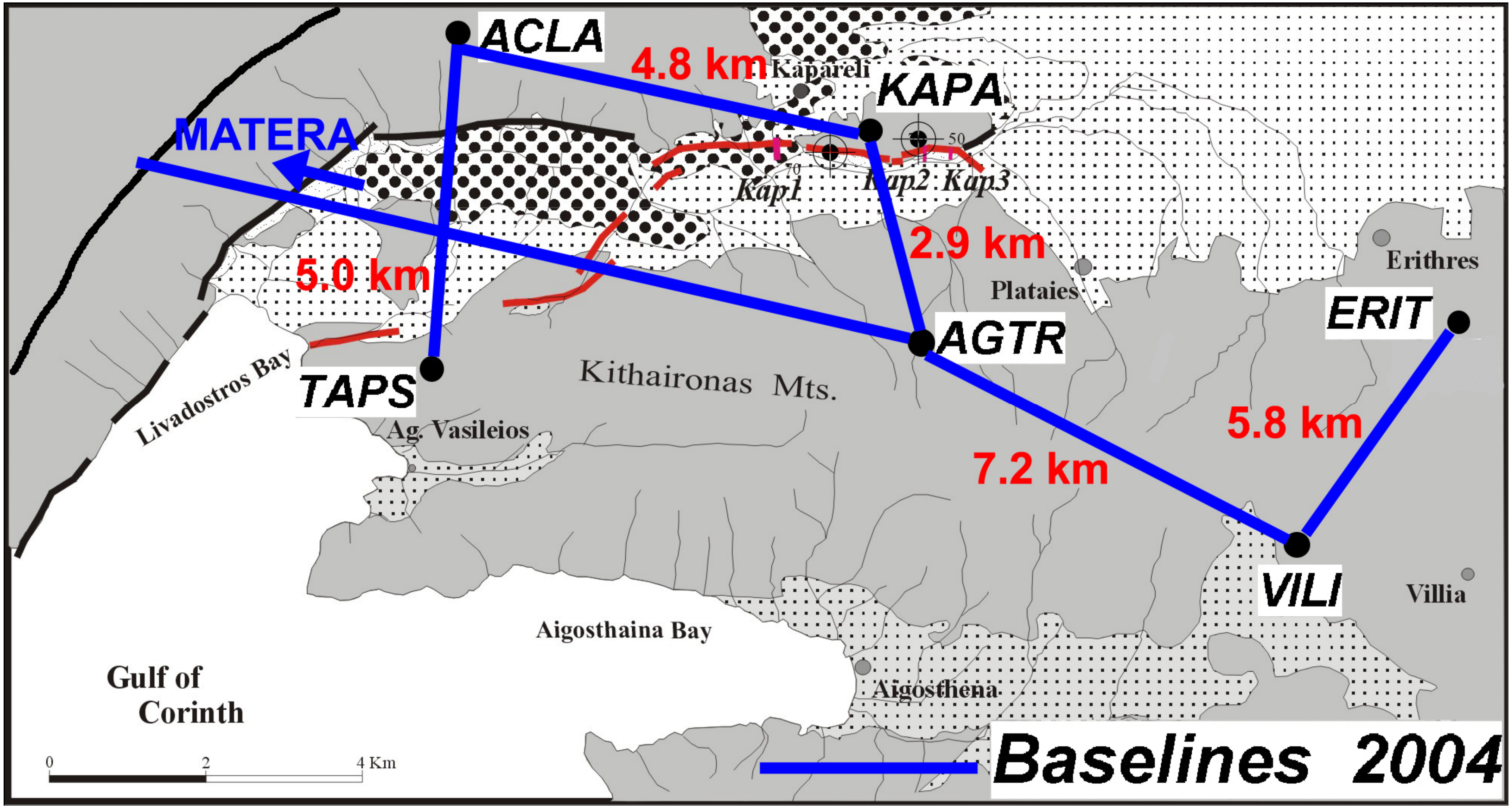

Fig. 6 Map of the study area showing May 2004 baselines of the GPS stations. Station AGTR was used as the base station.